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## Dynamic Characteristics for Traditional Wooden Structure in Korea by Using Impact Hammer Test

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### Abstract

This paper presents an investigation on dynamic characteristics of Heunginjimun through both ambient vibration and impact hammer tests. Heunginjimun, treasure No. 1 in Seoul, Korea, is a traditional wooden structure. Ambient vibration test is performed and spectrum analysis of time history is carried out to identify dominant frequency contents of Heunginjimun. Impact hammer test is undertaken to find the natural frequency of Heunginjimun with frequency response functions and phase information. Test results show that natural frequencies are 1.1Hz, 1.5Hz, 3.2Hz and 4.2Hz in two principal axes. Natural frequencies obtained by the tests are used to find the lateral stiffness of Heunginjimun. Simple dynamic models for Heunginjimun are suggested based on the moment resistance from joint beams and the restoring force due to column rocking. Lateral stiffness is found with identified natural frequencies and simple dynamic models.

**KEYWORDS:** Dynamic Characteristics, Stiffness, Wooden Structure, Restoring Force, Ambient Vibration Test, Impact Hammer Test, Column Rocking

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## 1. INTRODUCTION

Heunginjimun is one of 8 traditional gates, which were constructed in Lee dynasty. It is treasure No. 1 in Korea located in the eastern part of Seoul. Traffic roads are surrounded and two subways are passed under Heunginjimun. Therefore, Heunginjimun is exposed to vibration from traffics, as shown in Fig. 1.



Fig 1: Heunginjimun

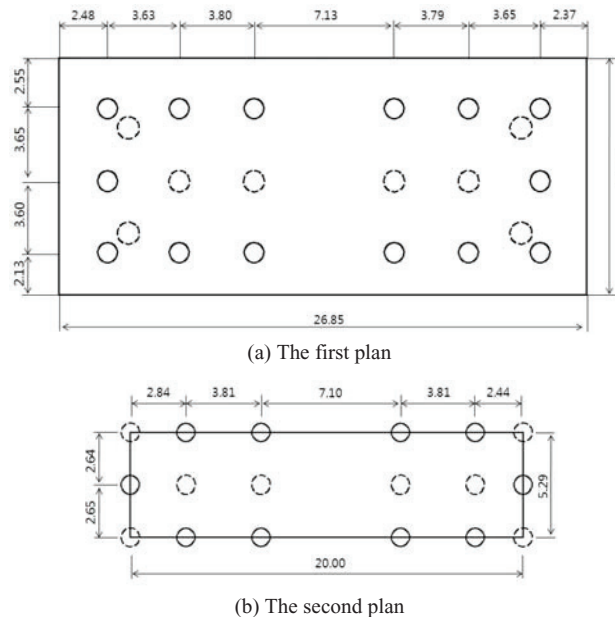


Fig 2: Plan of Heunginjimun (unit : m)

Traditional wooden structure in Korea, consists of columns, beams, bracket complexes, and roof tiles. They are connected simply without any metallic fasteners, such as column-base stone connection, bracket complex connection, and beam-column connection. Lateral stiffness of Heunginjimun comes from rocking columns and bending moments at column-beam joints with gravity force. The first story height is 5.84m and the second one 7.69m. The first story plan is 26.85m and 11.93m and the second one 20m and 5.29m, which is shown in Fig. 2. 32 columns are located in Heunginjimun. 14 of them are in the first story and 10 in the second story (solid circles in Fig. 2). Especially 8 are long columns of which height is as tall as two stories (dotted circles in Fig. 2), whereas others are short columns of one story height. Lots of short columns are connected with beams by simple joints, which induces lack of lateral stiffness.

Main purpose of the study is to identify whether Heunginjimun moves as one integrated structure or separate structures by applying ambient vibration and impact hammer tests. Natural frequencies are found, by which lateral stiffness is estimated from simply proposed models.

## 2. RESPONSE MEASUREMENT

### 2.1. Ambient vibration

Ambient vibration test is performed to figure out dominant frequency characteristics of structures from externally loaded small vibration (Kang, H. G. et al. 1999). 8 accelerometers are used, of which locations are in Fig. 3 with names of S1~S8. All the accelerometers are attached at the main columns in the middle to obtain data for natural frequency of x and y directions, which is shown in Fig. 4.

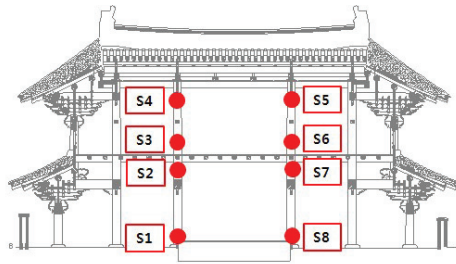


Fig 3: Accelerometer locations in section (Case 1)

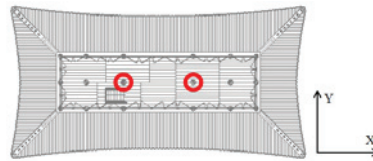


Fig 4: Accelerometer locations in roof plan (Case 1)

Second ambient test is carried out to identify the possibility of integrated motion of all columns by installing 8 accelerometers at the outer columns, of which location is 7.40m high from the ground.

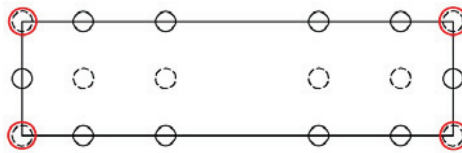


Fig 5: Accelerometer locations in the second plan (Case 2)

### 2.2. Impact hammer test

Dominant frequency contents are obtained from ambient test, which, however, give no information that they are natural frequencies. To confirm natural frequencies out of dominant frequency contents, impact hammer test is followed (Dossing, O. 1988). The test is performed by hammering the locations of

S3 and S6. Their forces and accelerations at the locations shown in Fig. 3 are obtained. Natural frequencies are identified with phase information at dominant frequencies.

### 3. MEASUREMENT ANALYSIS

#### 3.1. Ambient vibration

Figure 6 shows fast Fourier transformed accelerations at the locations of S4 and S5. Dominant frequency peaks in x direction are found in Fig. 6(a), which are 1.5Hz and 4.2Hz. Also, they are 1.1Hz, 1.3Hz, and so on in y direction. More peaks are shown in y direction than x direction since lots of joint from beams, columns, and brackets are in y direction, which are expected to cause local vibration.

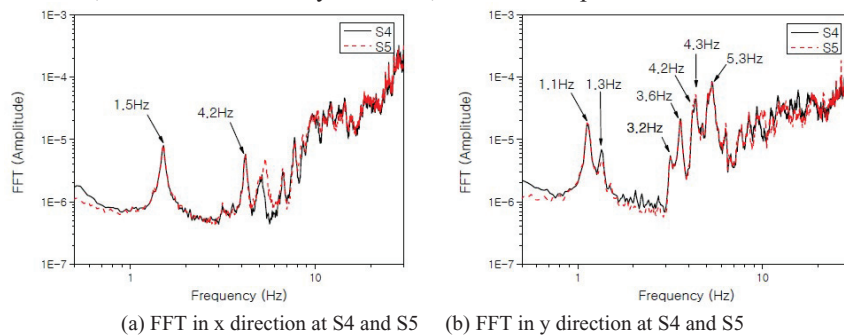


Fig 6: FFT from ambient vibration test (Case 1)

Figure 7 shows fast Fourier transformed accelerations at the outer columns, of which locations are in Fig. 5. Similar to the previous result, dominant frequency peaks in x direction are found at 1.5Hz and 4.2Hz. Also, they are 1.1Hz, 1.3Hz, and so on in y direction. Figures 6 and 7 indicate that most of peaks occur at 1.5Hz and 4.2Hz in x direction and 1.1Hz, 1.3Hz in y direction. Through the result of two ambient tests, It can be concluded that all the columns moves as one integrated body.

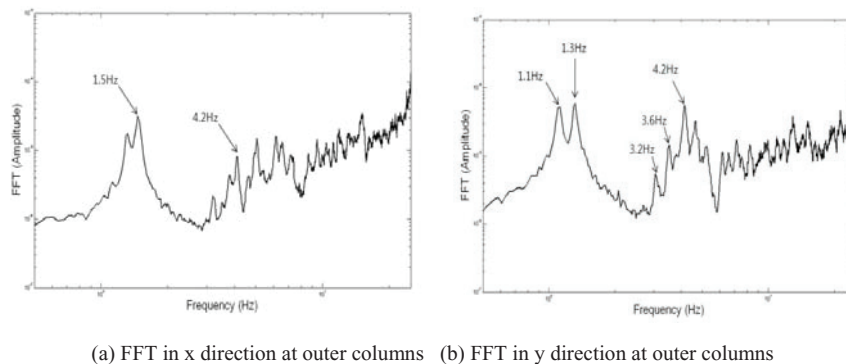


Fig 7: FFT from ambient vibration test (Case 2)

### 3.2. Impact hammer test

Figures 8 indicates frequency response function for the acceleration with input of hammer impact force (Ahn, S. J. et al. 2003). As shown in Fig. 8, peaks are found at 1.5Hz and 4.2Hz in x direction and 1.1Hz, 3.2Hz, and 4.2Hz in y direction.

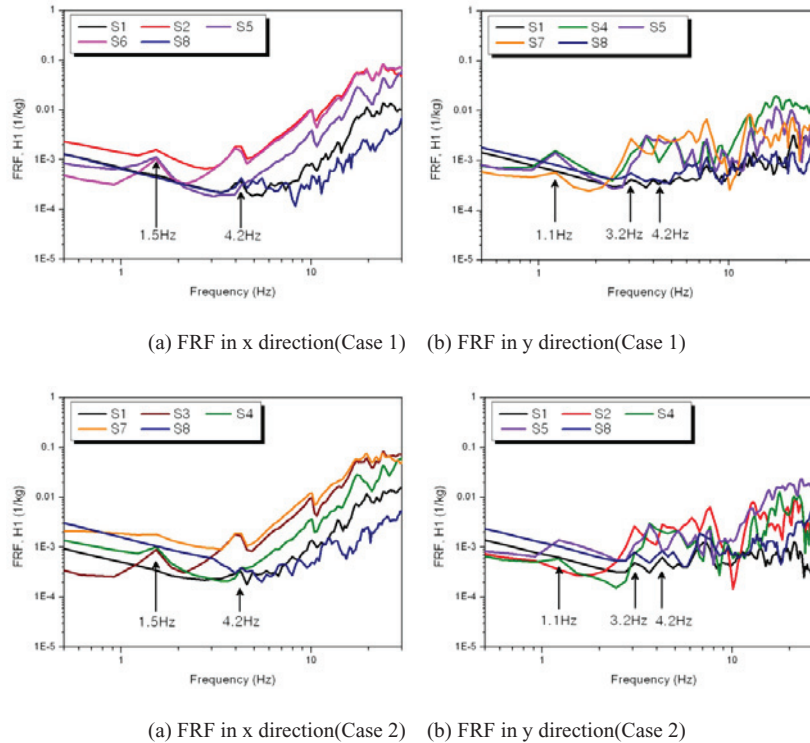


Fig 8: FRF from impact hammer test

Coherences are over 0.8 at the peaks at 1.5Hz and 4.2Hz in x direction and 1.1Hz, 3.2Hz, and 4.2Hz in y direction (Inman, D. J. 1994). Also phase shifts are found at the corresponding frequencies. It can be concluded that they are natural frequencies. Modes are estimated from frequency response functions obtained by impact hammer test. Each peak value is normalized by the largest one. It shows the mode shape of main columns in the middle at corresponding frequency. Figure 9 (a) shows the first mode in 1.5Hz and the second one in 4.2Hz in x direction. Figure 9 (b) the first one in 1.1Hz, the second one in 3.2Hz and the third one in 4.2Hz. It is found that two columns move similar at the same frequency. This indicates that columns move as one integrated body.

## 4. ANALYSIS MODEL

Dynamic loading should be applied to Heunginjimun to understand its characteristics such as natural frequency, mode, and lateral stiffness. Ambient vibration and impact hammer tests are used as external loading to Heunginjimun in this study. Since their magnitudes are so small that it is expected that Heunginjimun behaves linearly and the dynamic characteristics don't change. Small magnitude of

vibration don't cause column and beam joints to be loose so that the structural lateral stiffness maintains its own value. It is found that Heunginjimun moves as one integrated structure even if it consists of flexible joints of columns and beams. First and other higher natural frequencies are identified from experimental data of all columns. Lateral stiffness resulting from column rocking behavior, joint friction, and bending moments from connected beams can be figured out from identified natural frequencies by assuming appropriate models, which are named rigid body model and deformable body model.

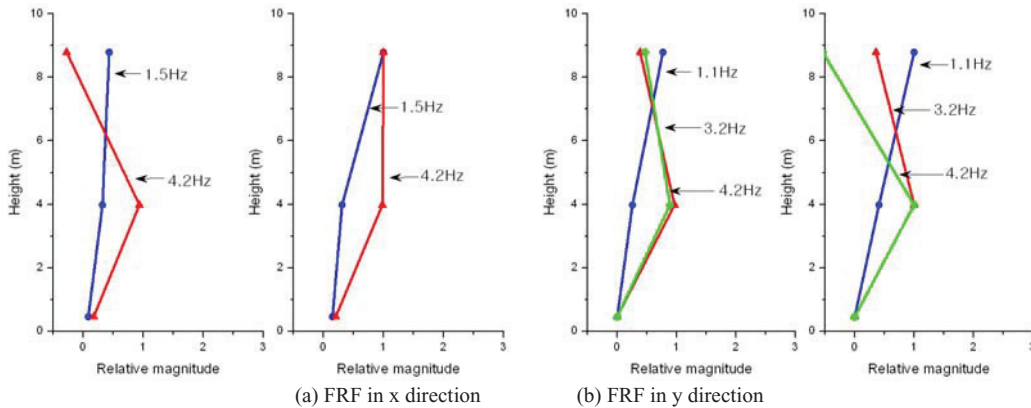


Fig 9: Mode shapes

#### 4.1. Rigid body model

The simplest analysis model of Heunginjimun is two-degree-of-freedom rigid body as follows in Fig.10. Restoring forces of each story are configured by lateral stiffnesses,  $k_1$  and  $k_2$ , which are for respectively, the first and second stories. Each story height is respectively,  $l_1$  and  $l_2$ . Lateral displacements for each story are denoted as  $Y_1$  and  $Y_2$ . Each story mass is estimated from the maintenance report of Heunginjimun, which are, respectively, 290 ton for the first story and 314 ton for the second story. Compressive forces  $P_1$  and  $P_2$  are regarded as gravity force acting on column, with which the model has restoring force when it moves.

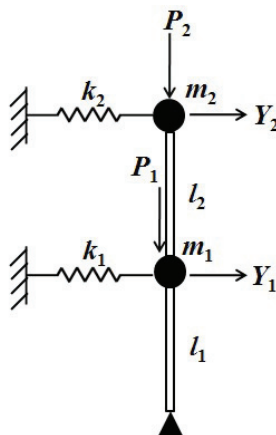


Figure 10: Rigid body model

Equation of lateral motion for the model is as follows (K. J. Bathe, 1996)

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{Y}_1 \\ \ddot{Y}_2 \end{bmatrix} + \begin{bmatrix} k_1 - \frac{P_1}{l_1} - \frac{P_2(l_1+l_2)}{l_1 l_2} & \frac{P_2}{l_2} \\ \frac{P_2}{l_2} & k_2 - \frac{P_2}{l_2} \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (1)$$

#### 4.2. Deformable body model

Another simple model is deformable body with two-degree-of-freedom. It is expected that input energy to Heunginjimun by external loading is transmitted to the energy by its kinematic motion without causing the columns, beams, and any other members to deform. Therefore, previously mentioned rigid body model is recommended. For most of building structures, their bodies are deformed to absorb input energy so that deformable body model is applied. To compare the result of rigid body model, deformable body model is taken into account in this study. Story masses and compressive force are same as those of rigid body model, whereas story stiffnesses are different.

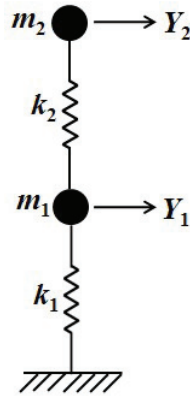


Figure 11: Deformable body model

Equation of lateral motion for the model is

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{Y}_1 \\ \ddot{Y}_2 \end{bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (2)$$

#### 4.3. Estimation of story stiffness

First natural frequency is identified from ambient vibration and impact hammer tests. It is expected that Heunginjimun behaves as one integrated structure's first and second natural frequencies. Story stiffnesses  $k_1$  and  $k_2$  are obtained from those frequencies by using eigenvalue equations as follows.

for rigid body model :

$$\det \left| -\omega^2 \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} + \begin{bmatrix} k_1 - \frac{P_1}{l_1} - \frac{P_2(l_1+l_2)}{l_1 l_2} & \frac{P_2}{l_2} \\ \frac{P_2}{l_2} & k_2 - \frac{P_2}{l_2} \end{bmatrix} \right| = 0 \quad (3)$$

for deformable body model :

$$\det \left| -\omega^2 \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \right| = 0 \quad (4)$$

where  $\det | \cdot |$  means determinant of matrix inside of  $| \cdot |$ .

Story stiffnesses are found from the eigenvalue equations as follows in Table 1.

Table 1 : Story stiffnesses (unit : tonf/cm)

	K <sub>1</sub>	K <sub>2</sub>
Rigid body model	208	28.9
Deformable body model	199	40.6

## 5. CONCLUSION

Investigation on dynamic characteristics of Heunginjimun is performed through both ambient vibration and impact hammer tests. Heunginjimun, treasure No. 1 in Seoul, Korea, is a traditional wooden structure. First, ambient vibration test is carried out and then frequency contents are identified from spectrum analysis. Next, impact hammer test is undertaken to confirm natural frequencies. The tests results show that same natural frequencies are found at the different columns, which gives information that Heunginjimun behaves as one integrated structure. Frequency response functions obtained by the tests are used to find the lateral stiffness of Heunginjimun. Simple dynamic models for Heunginjimun are suggested based on the moment resistance from joint beams and the restoring force due to column rocking. Lateral stiffness is found with identified natural frequencies and simple dynamic models.

## ACKNOWLEDGMENTS

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